Wireless Connectivity: An Intuitive and Fundamental Guide

Chapter 1: An Easy Introduction to the Shared Wireless Medium

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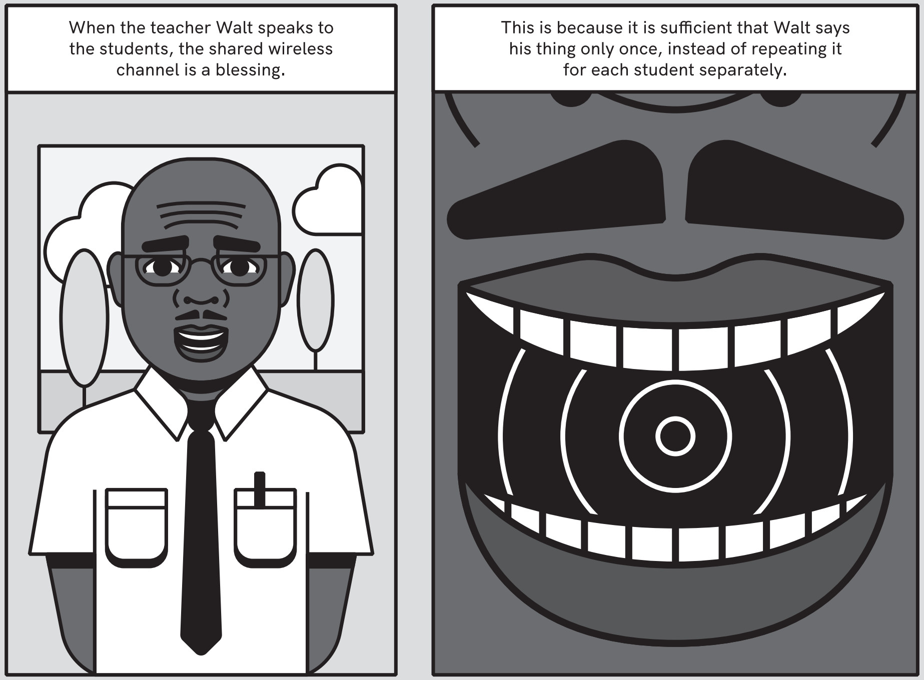
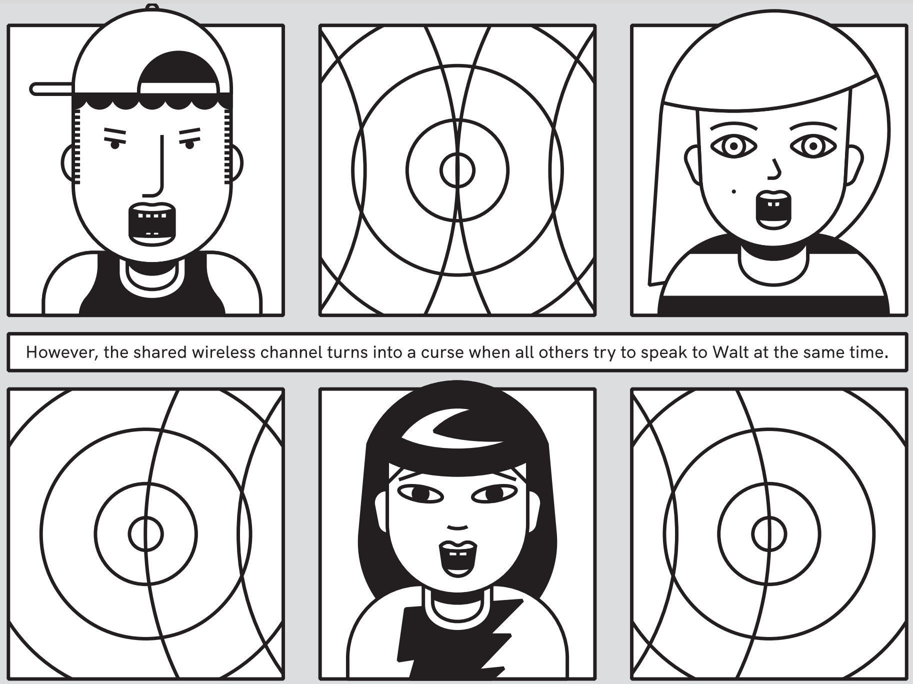
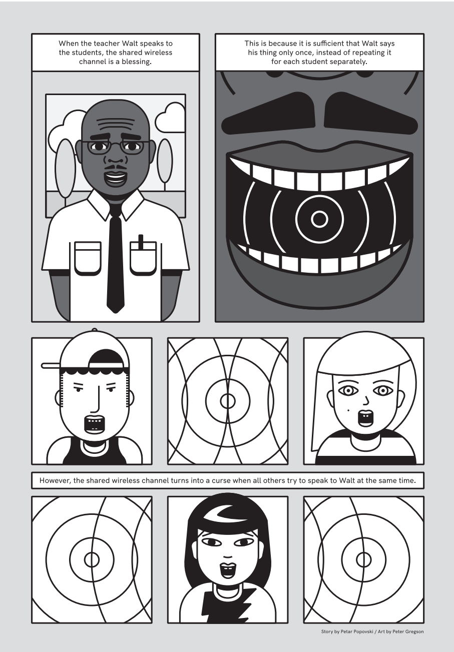
Chapters





Story by Petar Popovski / Art by Peter Gregson

Basic tradeoff in a shared communication medium



- It offers an advantage when the same information needs to be broadcasted to multiple receiving devices
- When these devices become transmitters, we need to mitigate interference

What will be learned in this chapter

- Specify a simple model for actors that share a communication medium
- Tackling the problems of “who talks first” and rendezvous
- How the assumption of half-duplex vs. full-duplex operation changes the design of a communication protocol
- Making a basic time-sharing communication protocol and illustrating the gap with the real-life operation
- A bit of advanced time-sharing: reservation and dynamic allocation

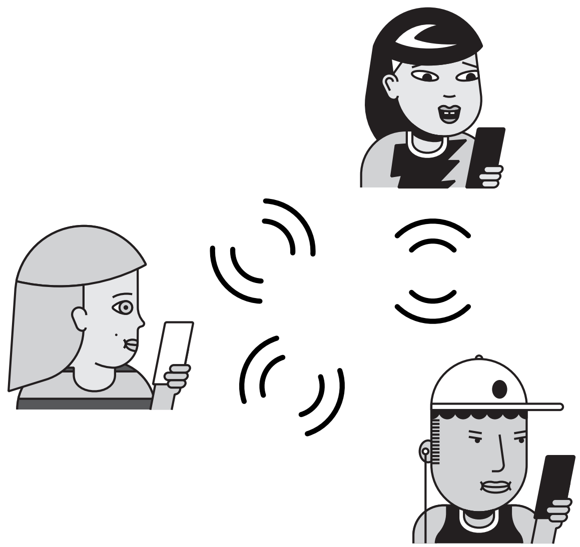
Making a simple wireless model

Shared channel and its characteristics

Sound waves and air analogy

Properties:

- Half/full duplex
- Broadcast
- Interference



Other assumptions

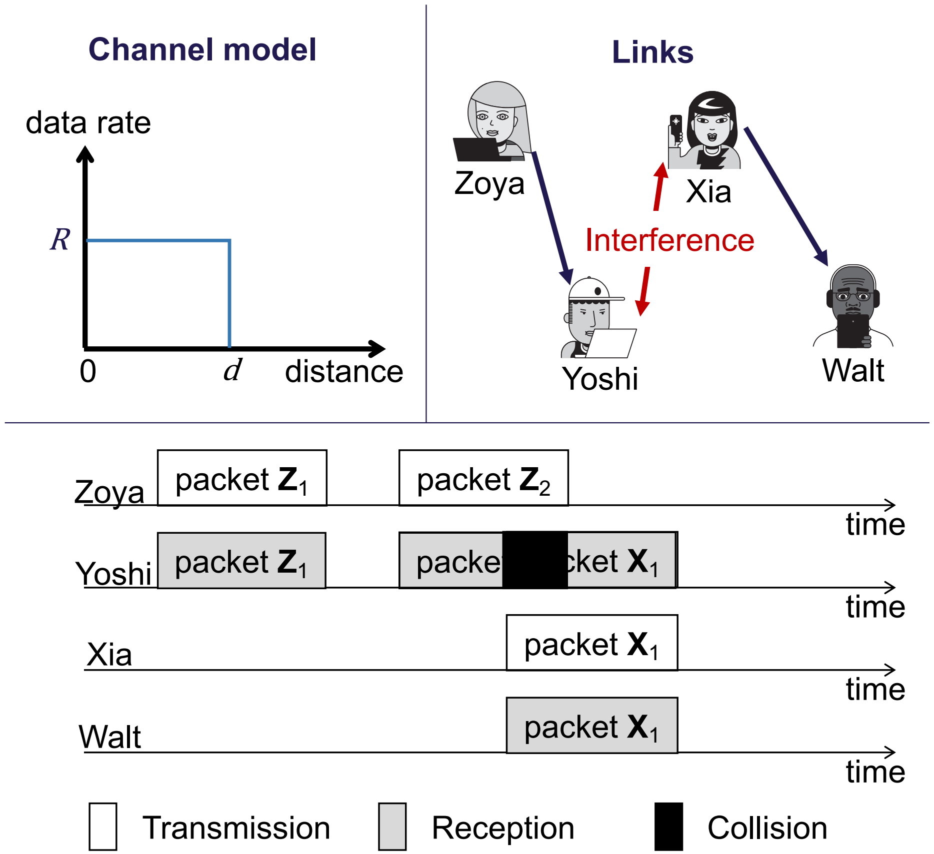
- Omnidirectional transmission and reception

A simple collision model

Special (pessimistic) case of
fully destructive interference

Successful transmission requires:

- Communicating devices need to be within a communication range
- No other simultaneous communication in receiver's range (zero tolerance to interference)
- If half-duplex: a receiver must be in a "listening state"



Wireless vs. wired

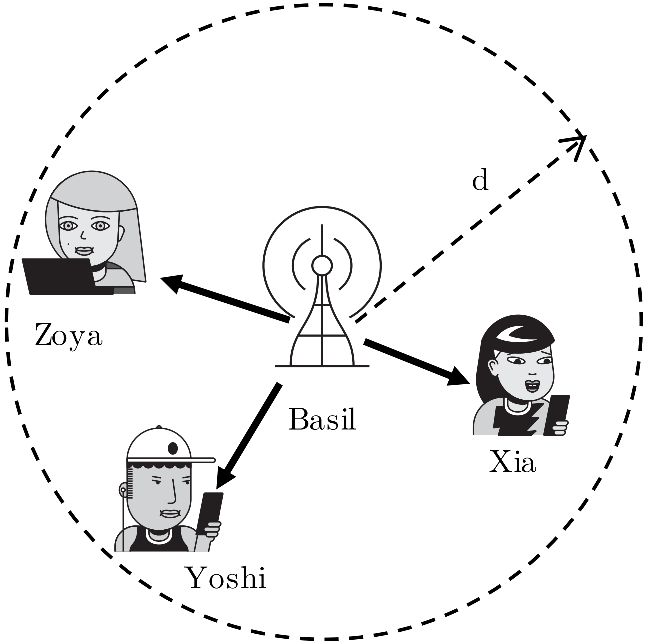
Wireless medium

- ✓ Flexibility to establish new connections
- ✓ High resource utilization
- ✗ Coordination is required to avoid interference
- ✓ Natural broadcast capability
- ✗ Extra mechanisms are required for security

Wired medium

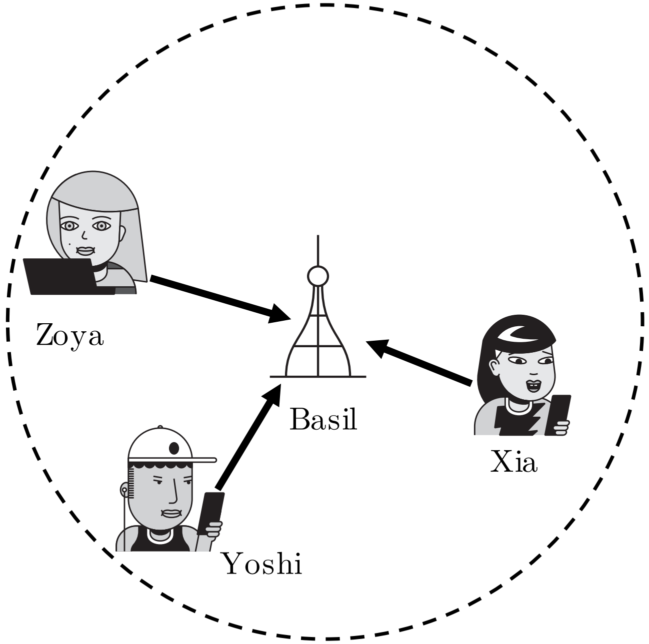
- ✗ New connections require new dedicated physical resources
- ✗ Low resource utilization
- ✓ No coordination is required, each user has its own medium
- ✗ Broadcast is expensive
- ✓ Has in a way “embedded” security

Broadcast and interference



broadcast

(cheap)



interference

(expensive to manage)

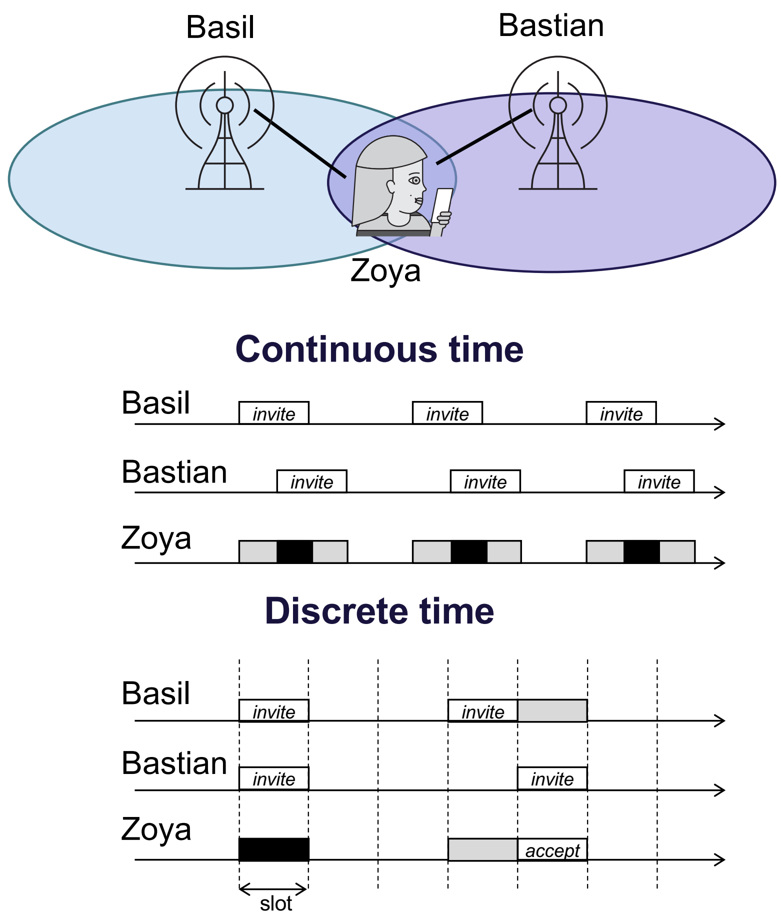
The first contact (1)

Who speaks first?

Ideally, some hierarchy is in place and the higher tier entity initiates communication

But what if more than one high tier entity is present?

Randomize the transmission of invites!



The first contact (2)

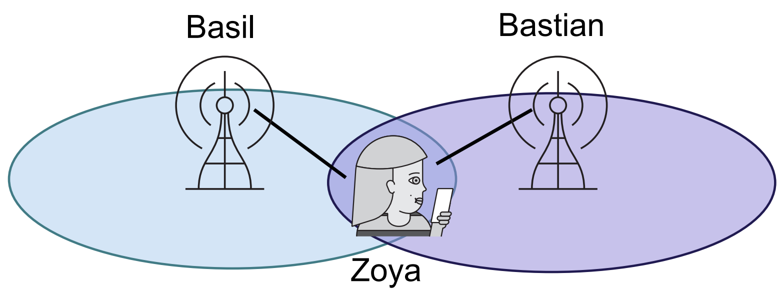
Rendezvous without coordination

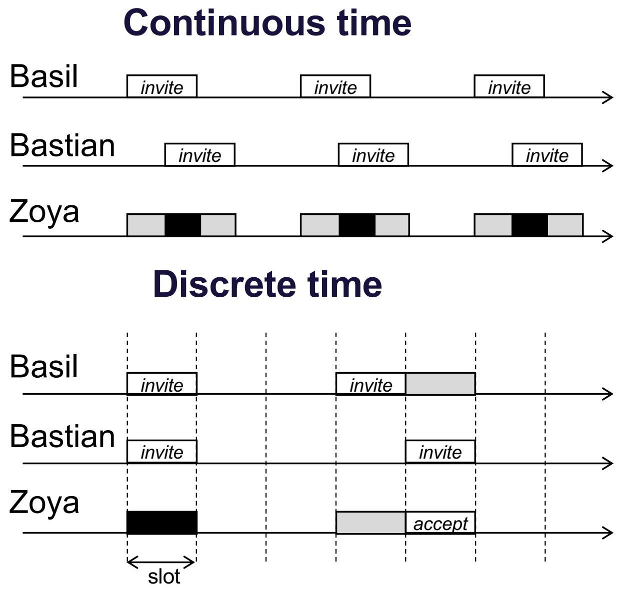
Devices that have not yet started communication are not synchronized

This reduces the chance of collision, as

Invites help Zoya adjust her clock

Note that "who speaks first?" is not a problem with full-duplex





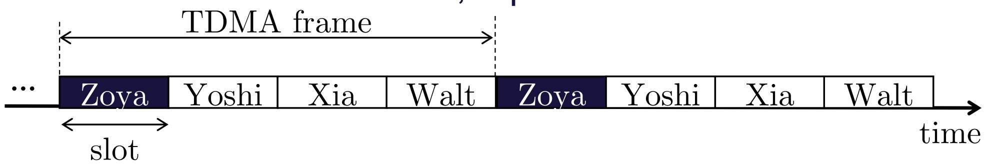
Multiple access with centralized control

The base station splits the resources when multiple users are involved

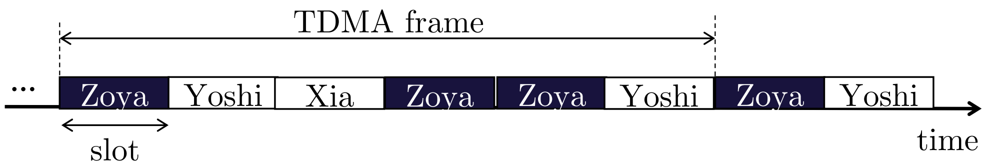
Time Division Multiple Access (TDMA): The entire communication medium is assigned to one user for a fraction of time; based on **frames** and **slots**

- ✓ Perfect for periodic traffic
- ✓ Little signaling is required
- ✓ Users can go to sleep in-between
- ✗ Inefficient if the users are inactive at their slots
- ✗ Loss of synchronization is critical

Periodic, equal allocation



Periodic, unequal allocation



Metrics for communication protocols

We define a ***logical channel*** for the users; see Zoya's in the figure

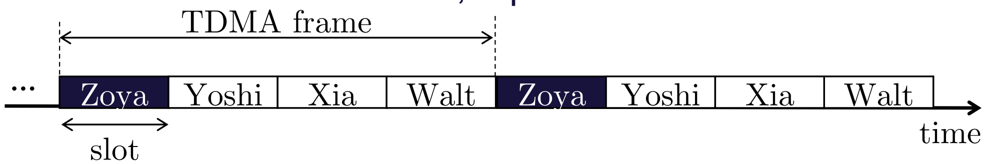
Effective data rate R_c is calculated from a nominal data rate R and slot duration T

Periodic, equal allocation

For K users over F observed frames

$$R_c = \frac{F \cdot R \cdot T}{F \cdot K \cdot T} = \frac{R}{K} \quad \text{[bps]}$$

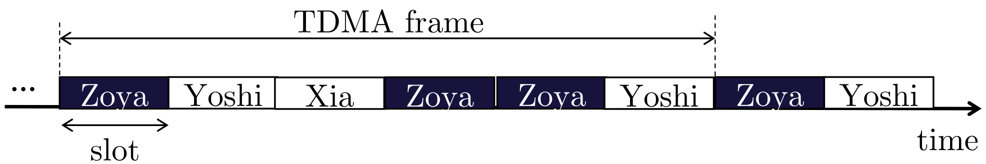
Periodic, equal allocation



Periodic, unequal allocation

$$R_c(T_R) = \frac{< \text{data bits sent over period } T_R >}{T_R} \quad \text{[bps]}$$

Periodic, unequal allocation

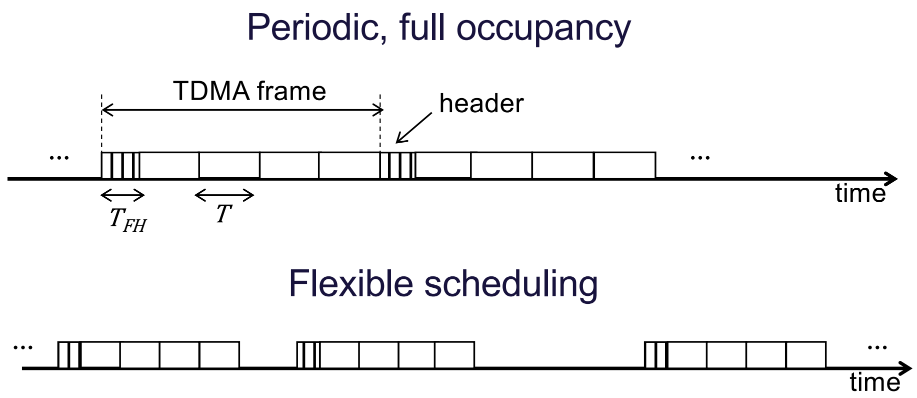


Signaling and metadata

These are needed to ensure a robust system operation

Adding a relatively short **header** at the start of the frame has numerous benefits:

- The base station can schedule the frame when needed
- Unsynchronized devices can align with the header
- A single bit can indicate uplink or downlink frame



Signaling and metadata: A simple system that (almost) works

Header types

- H_{00}: Link establishment frame
- H_{01}: Start of link termination; wait for indication from Basil
- H_{10}: Downlink (DL) frame
- H_{11}: Uplink (UL) frame

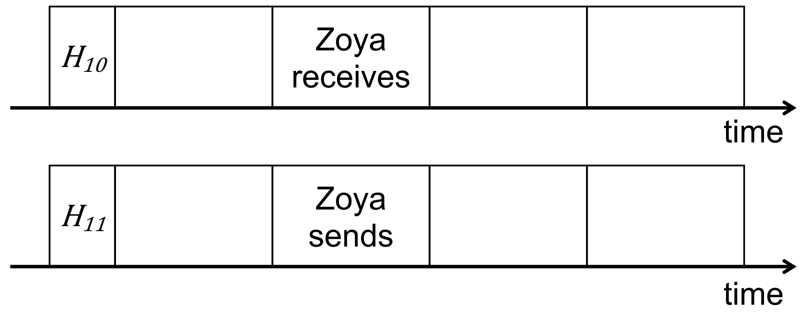
T_{FH}: Header duration

T: Frame duration

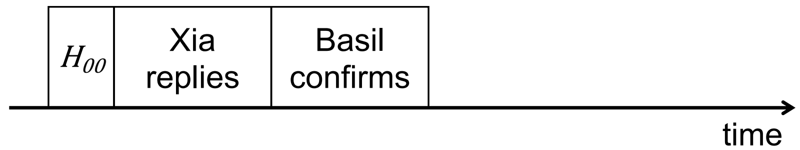
Assume $\frac{T}{T_{FH}} = \frac{k}{l}$

Slot as atomic unit with duration $T_S = \frac{T}{k} = \frac{T_{FH}}{l}$

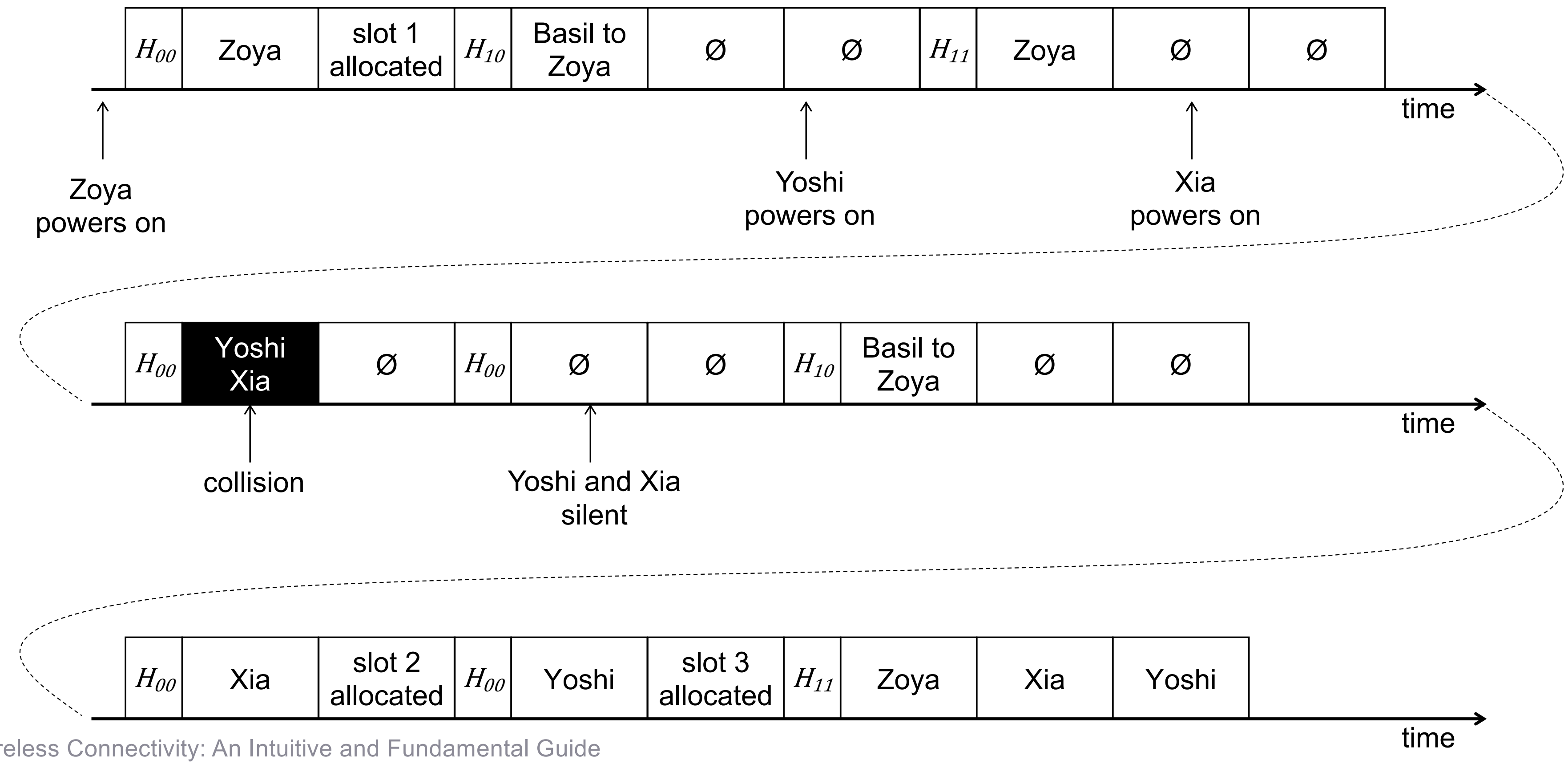
Uplink/downlink allocation



Link establishment



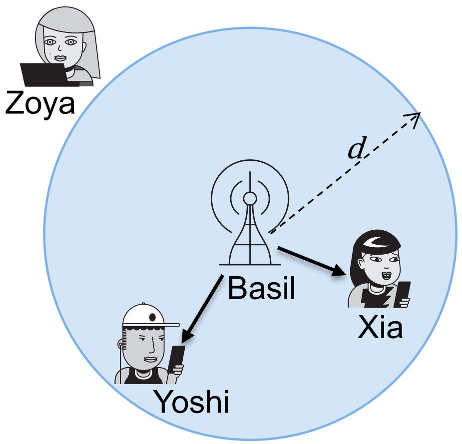
System in action with 3 terminals



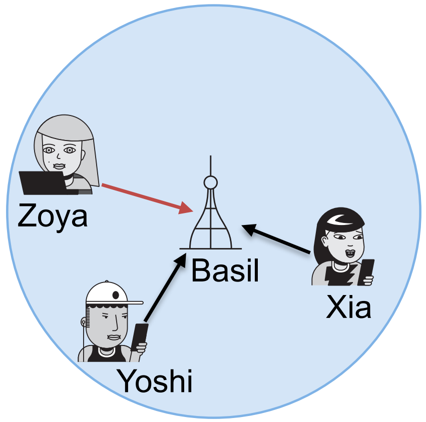
Still not a practical system

What happens if Zoya walks out of the cell?

Basil employs a timeout mechanism



What happens if Zoya returns, unaware that Basil changed the allocation?



Simple models should be enriched and become robust to (a lot of) practical issues

Making a dynamic TDMA (1)

User activity is rarely static

Distinctive user requirements

Trade-offs between **circuit switched** and **packet-switched** operation

Circuit-switched

- ✓ Minimal signaling
- ✗ Low flexibility

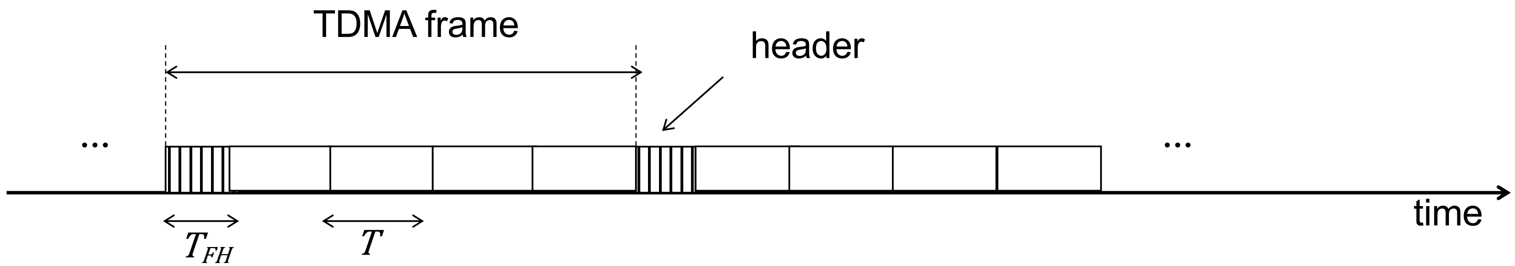
Packet-switched

- ✓ Dynamic allocation of resources
- ✗ High **overhead**

Increasing signaling increases flexibility

Making a dynamic TDMA (2)

How many bits are required to allocate K users in a frame with F slots?



There are K^F ways to allocate

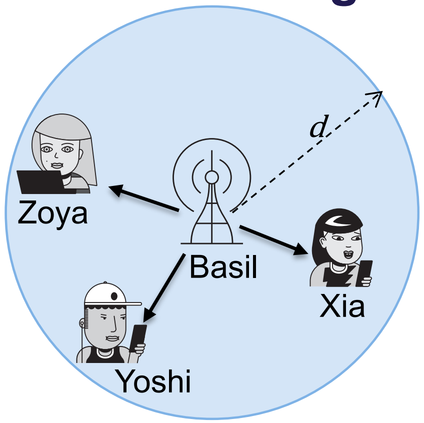
For a system that supports up to $K_{\max}$ active users, the frame header must contain at least $\lceil \log_2 K^F \rceil \leq F\lceil \log_2 K \rceil \leq F\lceil \log_2 K_{\max} \rceil$ additional bits

Example: For MAC address $K_{\max} = 2^{48}$

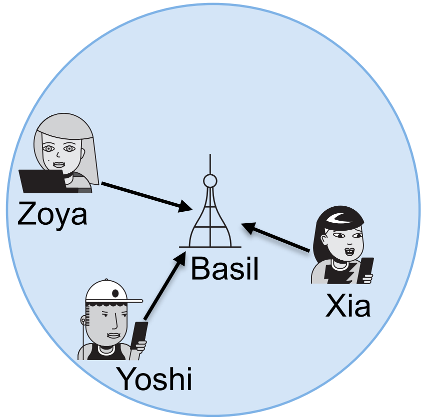
Making a dynamic TDMA (3)

How does Basil know how to assign resources?

DL is easy



UL is complicated…



Unless Xia's packets are perfectly predictable Basil can:

- Guess it (e.g. polling)
- Learn it (reservation)

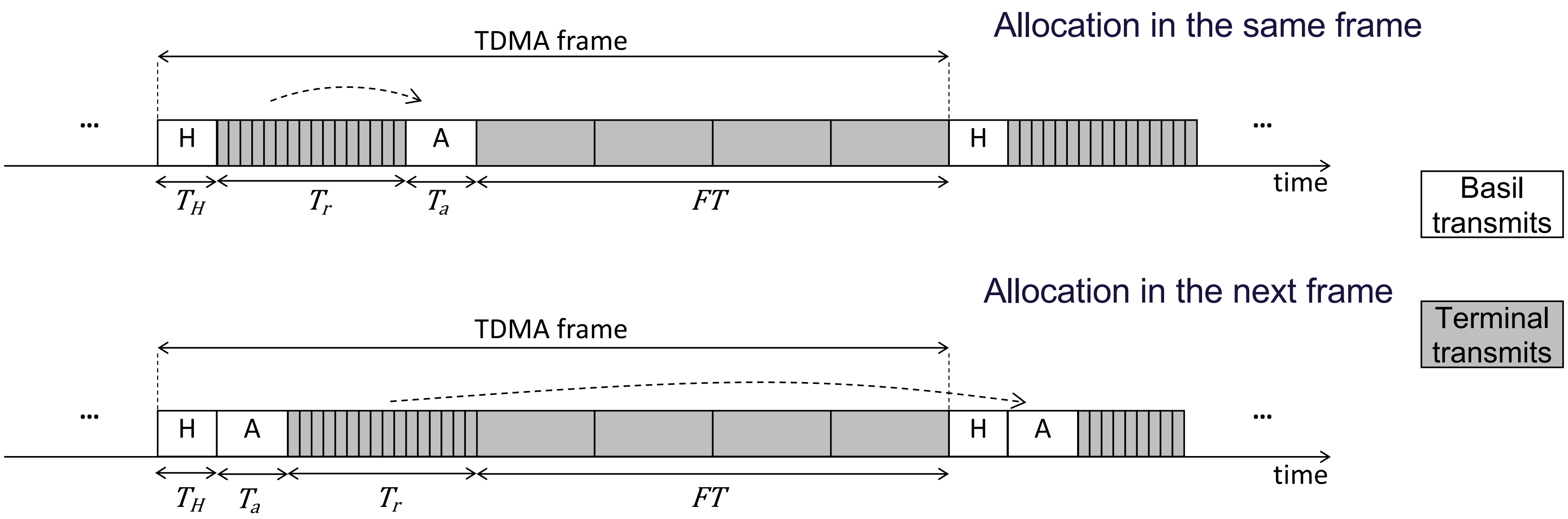
Analogy with conference scenario (however, this assumes an additional channel for signaling)

Short control packets and reservation

How does Basil know how to assign resources?

It allows all users to send **short** reservation packets ↑overhead

Allocates users according to their requirements



Evaluating overhead

We express overhead in relation to the duration of sending one bit

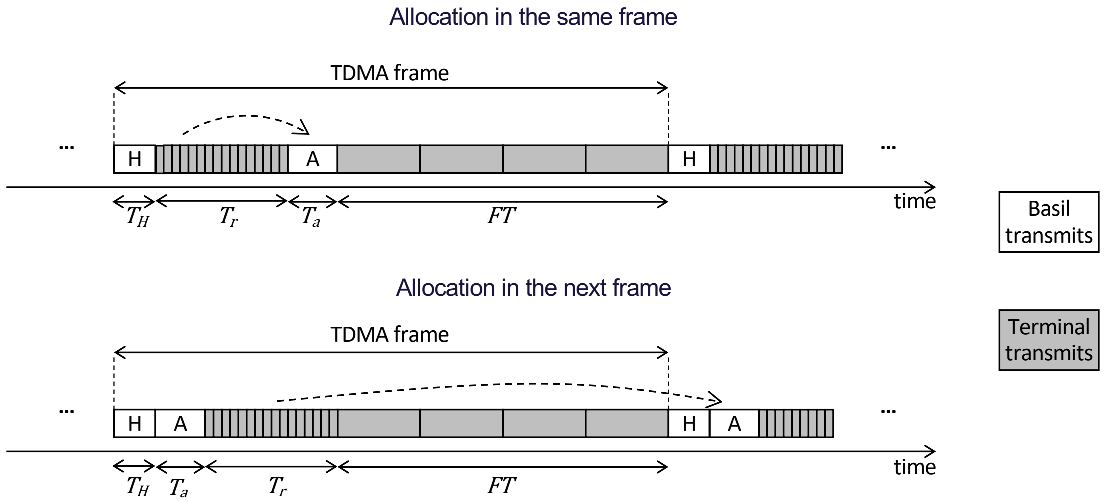
Data rate for a device that uses a single slot is $\bar{R} = \frac{RT}{T_H+T_r+T_a+FT}$

- For simplicity, all transmissions are made at a nominal rate of R bps
- A data packet with $D = RT$ bits
- A reservation packet with

$$r = \lceil \log_2(F+1) \rceil \text{ bits}$$

- An allocation packet with

$$a = F\lceil \log_2 K_{\max} \rceil \text{ bits}$$



$$\bar{R} = \frac{R}{\frac{2+r+a}{D} + F}$$

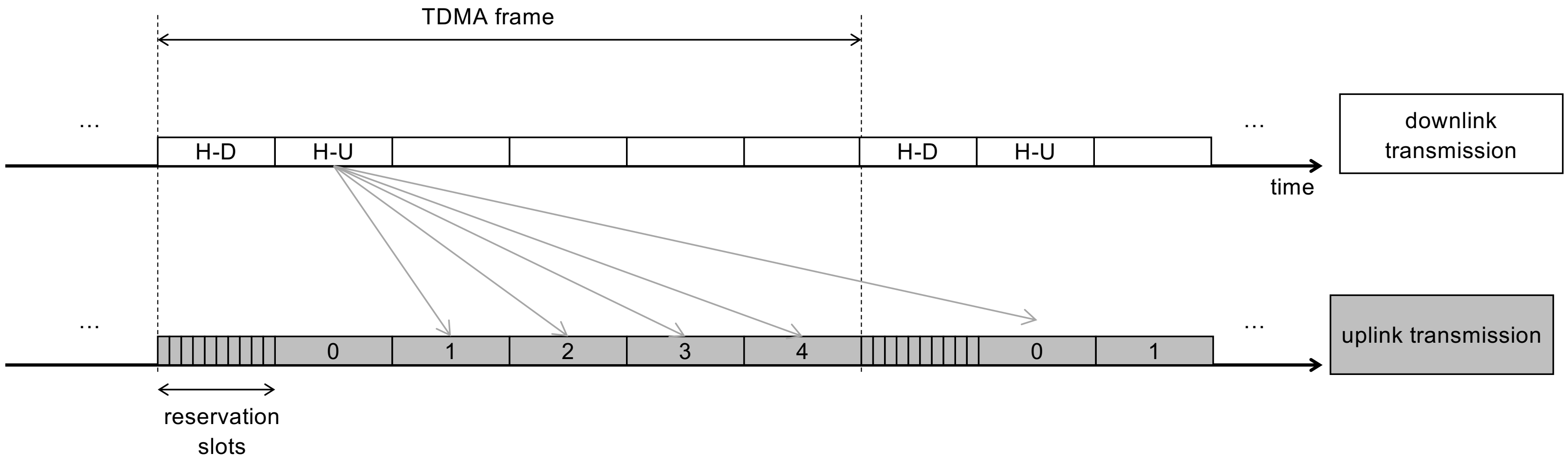
LARGE data packets improve **efficiency**

Half-duplex vs. full-duplex TDMA

Ideal switching between transmission (TX) and reception (RX) is not the case in practice: turnaround time

Avoid frequent turnaround to increase efficiency

Gain of full duplex: **lower** latency



Outlook and takeaways

- **Simple models** for **sharing** the wireless channel
- Broadcasting nature of the wireless medium: **interference = collisions**
- We can consider the **packet as an atomic** unit,
  but can also consider variable packet sizes
- Simple, yet practical, design principles for protocols
- Flexibility vs. overhead in protocol design
- Full vs. half-duplex: latency advantages in protocols